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Integrated Atomic Quantum Technologies in Demanding Environments: Development and Qualification of Miniaturized Optical Setups and Integration Technologies for UHV and Space Operation

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ABSTRACT

Employing compact quantum sensors in field or in space (e.g., small satellites) implies demanding requirements on components and integration technologies. Within our work on integrated sensors, we develop miniaturized, ultra-stable optical setups for optical cooling and trapping of cold atomic gases. Besides challenging demands on alignment precision, and thermo-mechanical durability, we specifically address ultra-high vacuum (UHV) compatibility of our integration technologies and optical components. A prototype design of an UHV-compatible, crossed beam optical dipole trap setup and its application within a cold atomic quantum sensor is described.

First qualification efforts on adhesive micro-integration technologies are presented. These tests are conducted in application-relevant geometries and material combinations common for micro-integrated optical setups. Adhesive aging will be investigated by thermal cycling or gamma radiation exposure. For vacuum compatibility testing, a versatile UHV testing system is currently being set up, enabling residual gas analysis and measurement of total gas rates down to $5 \cdot 10^{-10}$ mbar l/s at a base pressure of 10^{-11} mbar, exceeding the common ASTM E595 test.

Keywords: Micro-integration, Adhesive, Outgassing, Residual gas analysis, Quantum sensors, Environmental testing, Qualification, Ultra-high vacuum, Miniaturized optical setups, Cold atoms

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1. OPTICAL QUANTUM TECHNOLOGIES IN FIELD AND SPACE

Combining the current dawn of quantum technologies (QT) with the uprising prospects of small satellites is more appealing than ever[1]. It allows pioneering applications in the areas of timekeeping, optical communication, fundamental physics and sensing. This implies challenging requirements on the QT-devices regarding their mechanical and thermal stability, radiation hardness, and demands optimized size, weight and power (SWaP) budgets. In our work, we want to realize miniaturized, ultra-stable and ultra-high vacuum (UHV) compatible optical setups - an enabling technology for integrated optical quantum sensors in the field and in space.

These efforts rely on miniaturization of single components as well as subsystems micro-integration techniques. Such techniques are established at the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) to produce micro-integrated diode laser systems[2-4]. These modules proved their reliability within multiple sounding rocket missions[5-8] and are currently being qualified for the operation aboard small satellites[9]. Besides laser system and electronics, the very heart of an atomic quantum sensor is the atomic source. These often incorporate so-called atom-chips[10,11], which enable fast generation of ultracold atoms for e.g. sensing applications. To realize even more compact setups, we are developing micro-integrated optical setups directly on-chip. Our goal is to create setups for optical cooling and trapping close to the atom-chip surface. For such a setup, UHV compatibility must be ensured over a wide range of

application-driven conditions, and thus very low outgassing is vital. Hence, a qualification of the used optical elements and integration techniques regarding their outgassing, mechanical stability and thermal suitability is crucial.

1.1 Atom sources and in-vacuum optical traps

Within the KACTUS collaboration, we work on the integration of active and passive optical elements to form miniaturized atom traps with optimized SWaP budgets in UHV. The atom chip technology based on heritage from the sounding rocket mission MAIUS-I and MAUIS-II[12] is further developed by the Institute of Micro Production Technology (IMPT) and Leibniz University Hanover, Institute of Quantum Optics (LUH). A new atom chip design is displayed in Figure 1: on a Silicon chip Copper circuits with a diffusion barrier are deposited. They allow the generation of local magnetic fields to form e.g. a chip-based Ioffe–Pritchard trap[10]. With multiple atom-trapping and cooling mechanisms, a cold atom ensemble is generated in the atom chip's center.

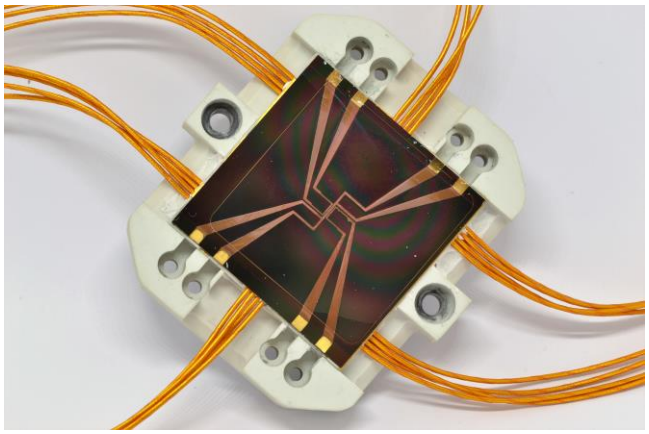

Figure 1. Atom chip based on a Si substrate, developed by the IMPT and LUH.

In parallel to the atom chip developments, we are looking into optical concepts to realize on-chip single beam magneto-optical traps (MOT) or crossed beam optical dipole traps (ODT). The prospective assembly requires very high stability and accuracy and thus calls for an integration of the optical elements on or near the atom chip within the atom chips vacuum system. Since the lifetime of the atomic ensemble is dependent on collisions with residual atoms in the vacuum system, an UHV environment and very low outgassing of chambers and components is mandatory.

A prototype design of a crossed beam ODT is displayed in Figure 2 (left). After a polarization-maintaining, single mode fiber collimator, the light is guided into a beam conditioning system. Here the diameter is increased from 600 µm to 2 mm using a telescope, and then separated into two orthogonal polarized parts with equal intensity. In both beams a spherical focusing lens (35mm focal length) is used to realize the crossed beam close to the atom chip surface. The size and geometry of this setup was chosen to be compatible with the atom chip assembly and could be mounted to the side of the chip. Within the chip center, the beams feature a waist radius of 20 µm and form a crossed beam ODT with an incidence angle of 45°. Based on this design, our current efforts focus at qualification of optical components and advancing adhesive micro-integration technologies according to the requirements summarized in Table 1. In Figure 2 (right) an established micro-integration setup used for diode lasers is displayed, which suits our accuracy demands. A further development and qualification of this integration technology towards UHV compatibility in application-relevant geometries and conditions is a main goal of this work.

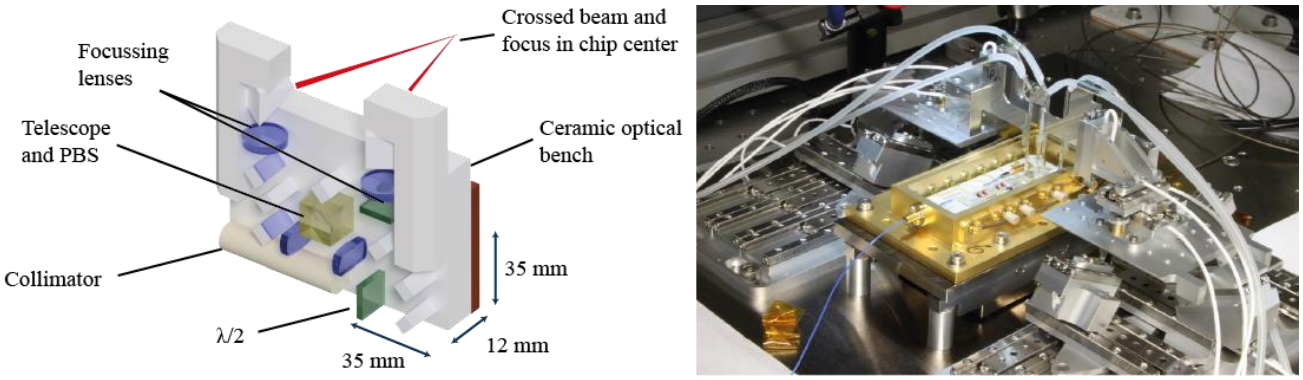

Figure 2. Left: Protype design of our miniaturized crossed beam ODT setup using in-vacuum optics. A crossed, focused beam (20 µm waist radius) in the chip center is generated by two end mirrors and focusing lenses. Right: Micro-integration setup established at FBH, which allows for the simultaneous integration of up to 4 components with 1 nm and 1 µrad relative position accuracy.

Table 1. Requirements for optical components and integration techniques for in-vacuum optical dipole traps.

Property	**Requirement**
Position accuracy of integration technique	100 nm and 5 µrad
Thermal cycling	ESCC 23201 6.4.2.4.3
Temperature during vacuum conditioning	Up to 150°C
Mechanical loads	30 g_{RMS}, 50 g DC accelerations
Outgassing of subassemblies	$<5 \cdot 10^{-10}$ mbar l/s, no volatile organics
Radiation hardness for LEO environments	10-15 krads

2. MECHANICAL AND ENVIROMENTAL ADHESIVE TESTS

The mechanical properties of adhesive micro-integration techniques are evaluated by adhesive tests. Glass test bodies with geometries applicable to micro-integrated setups are bonded with several adhesives to various substrates.

2.1 Atom chip substrates

The substrates used for the adhesive tests are currently developed by the IMPT for novel atom-chip assemblies. These substrates are silicon, silicon with 50 nm titanium as adhesive layer and 200 nm gold layer as seed layer. The metallization is applied by means of sputter deposition. For further planarization, the silicon chips can be coated with a 500 nm thick layer of non-doped spin-on glass NDG-5000 to form a silicon dioxide film.

These substrates are cut into 10x10 mm^2 squares to ease handling and to prevent systematic effects, e.g. surface contamination during long handling times, surface deformations or mechanical and thermal stress.

2.2 Sample setup and mechanical adhesive tests

For the mechanical adhesive tests precision glass blocks with a footprint of 2x4 mm^2 are manufactured. While simple blocks are sufficient for shear strength tests, a trapezoidal shape is used for tensile strength tests. A surface polishing (polishing grade P1) is applied to the faces to ensure reproducible UV transmission to the adhesive. The face in contact with the adhesive is in addition to the surface polishing of very low roughness ($R_t \leq 50$ nm), which leads to an equal surface area for all glass blocks and hence to comparable results.

The relevant adhesive systems are one or two component epoxy resins common in optomechanics industry, which we expect to meet the demands stated in Table 1. Epoxies are a suitable choice regarding mechanical and thermal properties[13], outgassing and shrinkage. To set-up a micro-integrated optical setup, an initial UV curing to fix the

component is required. A subsequent thermal cure can be realized and might benefit the above-mentioned properties depending on the epoxy's curing mechanism.

Figure 3 shows the sample setup procedure. A glass test block is attached to the setup with a local position accuracy of 1 nm and 1 µrad. It is aligned parallel to the substrates surface, which is fixed on a holder by a vacuum tweezer. After touching the substrate with the test block to determine the zero-gap position, the block is moved away vertically and then laterally. Adhesive is applied, the test block is moved back to its initial position and the adhesive gap precisely set up between 10 and 30 µm. For adhesive application a pneumatic dispenser system is used, which allows for the precise application of adhesive down to 20 nl volume depending on the viscosity. A calibration measurement is performed for each adhesive batch. The adhesive is then cured by an UV lamp, which is shown in Figure 3 on the right. A subsequent thermal cure up to 200°C can also be performed in an oven with adjustable heat-up and cool-down ramps.

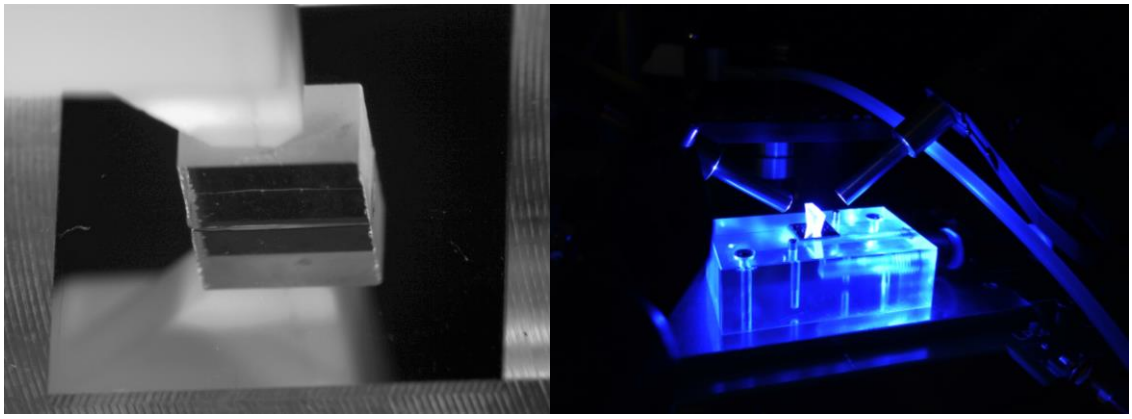

Figure 3 Left: microscope picture of the adhesive test samples during integration. A glass block of 2x4 mm^2 footprint is adhesively attached with a precision micro-integration setup to a 10x10 mm^2 Si wafer. Right: UV curing of adhesive samples.

Tensile and shear strength testing is performed at IMPT to evaluate the bond strength. Test facilities involve a ROYCE Instruments SYSTEM 552 shear strength tester and a Mecmesin MultiTest 2.5 - *xt* tensile strength tester. Future tests involve adhesive aging, which will be investigated by thermal cycling according to ESCC 23201 6.4.2.4.3 (a variation of MIL-STD-883 Test Method 1010.8 A) with a Vötsch VT^3 7006 S2 and subsequent tensile and shear strength tests. Furthermore, radiation hardness will be tested by exposure to a C60 gamma source with ionizing doses of 10-15 krads, resembling LEO conditions.

For these mechanical and environmental qualification tests, we are currently setting up samples and performing first runs. In parallel, a test setup for the vacuum qualification is assembled and commissioned.

3. UHV QUALIFICATION

One core aspect of our work is the design of a versatile UHV qualification setup, which enables us to investigate the UHV compatibility of integration technologies, optical components and medium-sized assemblies. The requirement of ultra-low outgassing primary stems from the degrading lifetime of cold atomic samples due to collisions, as outlined in Section 1. Furthermore, damage on optical components caused by volatile organics will limit the reliability and has been investigated extensively[14].

The common standard regarding outgassing measurements in space and aviation industry is the ASTM E595. Here, a mass loss measurement is performed: a sample is placed in a vacuum of at least $6 \cdot 10^{-5}$ mbar and heated to 125 °C for 24 h. A collector cooled to 25 °C is placed in front of the sample furnace. With precision balances, the mass of the sample and the collector is measured before and after the vacuum treatment, and the total mass lost (TML) and collected volatile condensable materials (CVCM) determined.

While this measurement gives a good assessment about the outgassing of e.g. adhesives or coatings, its resolution is limited to about 10^{-5} mbar l/s for reasonable measurement times. Furthermore, the measurement is not gas specific. Our demands of UHV compatibility require a resolution of gas rates which are 4 to 5 orders of magnitudes smaller. This is of rising importance, not only within integrated optical quantum technologies, but also for e.g. semiconductor

manufacturing. The newly released ISO/TS 20177:2018 treats outgassing measurements and aims at the standardization of instrument design, measurement and error estimation.

The design of a multipurpose in-house qualification apparatus capable of measuring ultra-low outgassing rates was necessary, since there is no significant literature data regarding the outgassing rates of optical components and adhesive integration technologies.

3.1 Fundamentals of outgassing rate measurements

Although there are many methods for the measurement of low outgassing rates in the high vacuum regime[15,16], most of them are a modification of either the pressure rise or the throughput method. Our setup relies on the latter method: a measurement chamber with a sample is continuously pumped through an orifice of known conductance C. By measuring the pressure p_1 in the sample chamber upstream of the conductance and p_2 in the downstream pump chamber, the outgassing rate in the sample chamber can be calculated by

$$Q=C\cdot(p_1-p_2). \quad (1)$$

The measurement resolution is limited by the background outgassing rate caused by the vacuum system, internal components and the measurement equipment. Further influence on the measurement process comes from the re-adsorption of outgassed molecules on the chamber walls and systematic effects of the gauges themselves.

3.2 A versatile UHV qualification setup

Our aim was to design a measurement setup that enables the measurement of total gas rates down to $5\cdot10^{-10}$ mbar l/s at a base pressure of 10^{-11} mbar. At the same time a fast sample exchange should be possible to facilitate fast set-up times as well as measurements of the background outgassing rate and species before/after each measurement without the need for breaking the vacuum.

The design of the measurement apparatus is shown in Figure 4. A two-stage transfer system for samples of up to 65x65 mm^2 footprint is facilitated by two magnetically coupled power probes. Vacuum separation of both stages is realized with a CF100 gate valve. The load-lock part of the transfer system is vented for sample exchange and then pumped down to below 10^{-4} mbar. A sample, mounted on a sample holder, is transported into the transfer chamber by the first power probe. In this chamber, the sample holder is passed to the second power probe, which then either transports the sample to a sample heater for pre-conditioning or directly to the sample receiver in the measurement chamber. A CF 100 gate valve also separates the measurement and transfer chamber.

The measurement chamber consists of two separate parts, the sample and pump chamber, which are connected through an orifice of known conductance. The pump chamber is continuously pumped by a 300 l/s turbomolecular pump (TMP). Bayard-Albert (BA) ionization gauges in both chambers allow for the determination of the outgassing rate in the sample chamber following Equation 1. A bypass between both chambers is implemented with angle valves and allows a faster pump-down of the measurement chamber during conditioning and after sample investigation. Furthermore, a residual gas analyzer (RGA) for masses up to 200 amu is installed within the bypass, enabling the measurement of partial pressures and thus outgassing species on both sides of the conductance element. The measurement chamber features various ports for optical access to the samples, electrical feedthroughs, connections to standard leaks and a gas dosing system. The last two are used for the calibration of RGA and conductance element or to generate custom residual gas atmospheres.

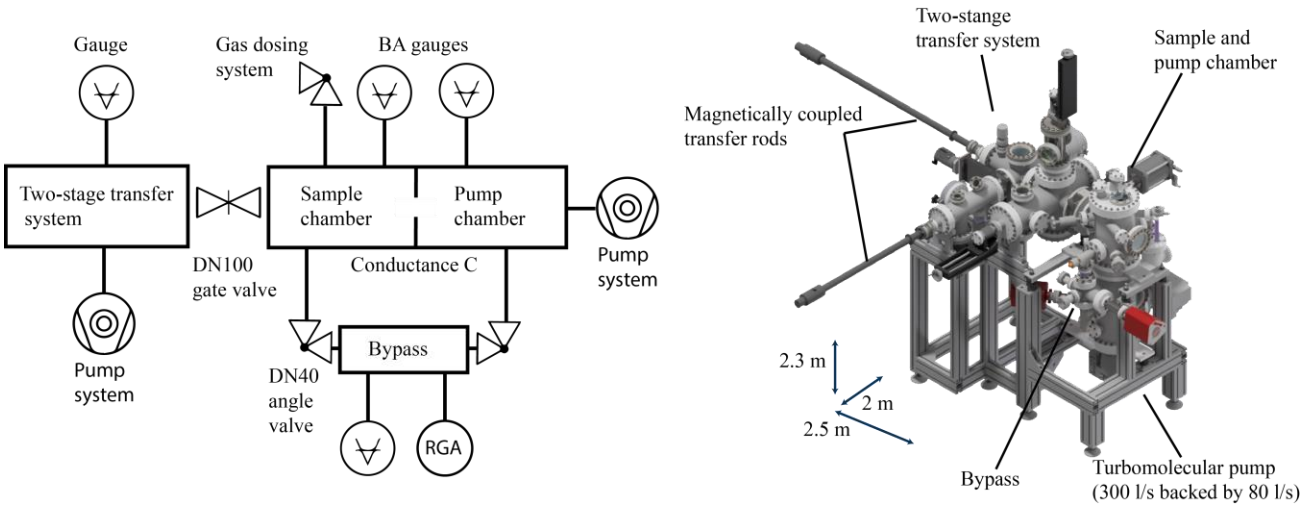

Figure 4 Schematic diagram of the outgassing setups measurement part on the left. On the right, a CAD rendering with the functional parts of the setup is depicted.

Sample heating up to 200 °C will be facilitated in the sample receiver via inert Pt heating elements in non-porous alumina ceramic. In combination with the outgassing measurement, this will allow for the development of optimized conditioning schedules and unique thermal cycling studies. Furthermore, electrical connections to the sample carrier will be available, which allows for the operation of electronic components. Together with the adaptable residual gas atmosphere, unique lifetime studies will be possible.

The background outgassing of the setup, the gauges and RGA determines the lowest resolvable total gas rate. Hence, much effort was put in the surface finishing process of the vacuum chambers to reduce the outgassing. The heating element and the materials of the sample receiver are chosen to reduce background outgassing as much as possible. We expect the limiting factor to be the BA gauge and expect its outgassing to be around $5 \cdot 10^{-10}$ mbar l/s according to metrological characterization of comparable gauges[17].

3.3 Status and outlook

Successful first tests and characterizations of the setups components (e.g. RGA, heater, gauges) were conducted and the overall setup is currently being assembled. After commissioning the overall system with transfer and measurement system separated, both parts will be connected, and the measurement equipment and gas dosing system characterized. Following this, we will begin to investigate the adhesives subject to the mechanical tests of Section 2. We expect to benefit from the additional effort put into the sample transfer system by reduced set-up times.

In parallel, studies of optical key-components are planned. These include fiber collimators and feedthroughs, optical fibers, laser and photo diodes, acusto- and electrooptical modulators and TEC elements. Furthermore, an investigation of materials and substrates for the atom chip development is foreseen, since some of the bonding and planarization techniques, might lead to an increased outgassing of atom chip assemblies.

4. SUMMARY AND OUTLOOK

We want to investigate promising adhesives regarding their mechanical, thermal and vacuum properties, as well as environmental aging in application-relevant geometries and material systems suitable for micro-integration. An in-depth study is planned to systematically study the various influences on crucial properties such as surface cleaning processes (e.g. oxide-plasma cleaning), different curing schedules (UV intensity and duration, thermal curing), adhesive application, gap sizes or accuracy of component mixture ratio. Environmental aging with thermal cycles and radiation exposure will complete our studies of adhesive integration, which is a key technology for miniaturized, optical systems in the next generation of optical quantum sensors.

Our UHV compatibility studies of adhesives are planned to surpass the common ASTM E595 standard. After final assembly and commissioning of our versatile UHV testing setup, the fast sample exchange and measurement system will also facilitate the qualification of optical components (e.g. fiber collimators, coatings, diodes) and complete assemblies

as for example our ODT setup shown in Figure 1. Further applications include the investigation of advanced manufacturing technologies, such as additive manufacturing for in-vacuum metal-alloy based components.

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